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Search for the intermediate-scale anisotropy of the cosmological background radiation

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We measured the anisotropy of the cosmic background radiation at the angular scale of 2° in the millimetric wavelength region, in the course of the NASA-ESA ASSESS II Mission. We set upper limits on the anisotropy in several sky regions, the most stringent one being $\Delta T/T < 3\times 10^{-4}$ at one standard deviation. Cosmological consequences of this measurement are discussed. Anisotropies as large as $\Delta T/T = 7\times 10^{-3}$ have been detected close to the galactic plane, and we tentatively interpret them as galactic dust emission.

I. INTRODUCTION

Since the discovery of cosmic background radiation[1] considerable effort has been expended[2-10] to detect its anisotropies at angular scales $\Theta \lesssim 1°$. The detection of small-scale anisotropies would be of cosmological interest, since they should carry information about the primordial perturbations of matter (sound waves and whirl motions)[11-17] from which galaxies, clusters, and superclusters are supposed to originate,[18] and about metric perturbations (gravitational waves) extending over cosmological distances.[16,19-21] No measurement of the cosmic background (CB) anisotropy has been performed at intermediate scales, namely $1° < \Theta < 180°$. Although estimates of the cosmic background anisotropy at scales less than 180° may be inferred from previous large-scale measurements[22] they turn out to be of the order $\Delta T/T \leq 10^{-2}$ at angular scales of 10°. Since the characteristic length of the corresponding perturbations ($\gtrsim 10^2$ Mpc at the present epoch) is larger than the typical scale of rich clusters, such anisotropies are not likely to give us information on the early history of the observed bound systems. However, it has been recently claimed[23] that there is indeed astronomical evidence for the existence of structure at scales of ~500 Mpc, larger than suspected so far, so that we are compelled to check whether CB anisotropies exist at the corresponding angular scales. Moreover, the detection of such anisotropies would be of special importance for the following reason. If the proper length of perturbations was larger than the optical horizon at the recombination of the primeval plasma, i.e., at red-shift $z = 10^3$, the primordial perturbation spectrum was not affected by dissipative processes throughout the plasma era. Assuming that the last scattering of the CB photons occurred at red-shift $\simeq 10^3$, the radiation anisotropy should give direct information on such primordial spectrum at angular scales $\Theta \gtrsim 2\Omega_0^{1/2}$, where Ω_0 is the usual density parameter. Thus measurements at scales larger than ~1° would give us information about the state of the universe at the very beginning. According to the "philosophy" of chaotic cosmology,[24] causally unconnected regions of space should exhibit physical parameters widely different from each other. Therefore one would expect to find CB anisotropies resulting from large perturbations at $\Theta > 1°$. Stringent upper limits on the background anisotropy at such scales would constitute a strong argument against chaotic cosmology.[25]

Even if the radiation distribution turns out to be highly isotropic at all scales, the spectrum of the anisotropy (considered as a function of scale) may have some structure, showing the influence of dissipative processes at lower scales. If the CB radiation was scattered by a reheated plasma at red-shifts $z \simeq 13\Omega_0^{-1/3}$, the anisotropy at scales of a few degrees would carry information about the structure of the cosmological matter at relatively low red-shifts; however, at scales $\Theta \gtrsim 20°\,\Omega_0^{2/3}$ one would certainly observe the spectrum of the primordial perturbations. A detailed investigation of the angular anisotropies in the 1°–20° range might enable us to decide on the epoch at which the radiation began to propagate freely. This is still a fundamental unanswered question in cosmology.[26]

In the present paper we describe a measurement of the CB anisotropy at $\Theta = 2°$, in the 500–2000 μm wavelength range. The convenience of performing measurements in the millimetric region should be emphasized.[9] The use of broadband detectors and the existence of a maximum of the differential brightness near 1 mm allows a sensitivity of order 10^{-4} with a reasonable integration time. However an important limitation of infrared (IR) measurements of the CB anisotropy could be local emission in our galaxy.[27] The IR radiance of molecular clouds has been found[28,29] to be of the order of 10^{-8} W cm^{-2} sr^{-1} at galactic longitude ranging between $-10°$ and $+55°$. However the contribution of dust clouds to the background anisotropy in the 500–2000 μm range is under question.[27] Extensive investigations at several galactic latitudes are desirable in order to be able to separate cosmological anisotropies from dust emission. A few signals detected close to the galactic plane can be tentatively interpreted as dust emission. This point is discussed in Sec. III.

The experiment was performed on board a NASA Convair 990 during the ASSESS II Mission. The measurements and the in-flight calibration were done in the course of 10 flights in May and June 1977. The choice of on-board operation was dictated by the following reason: Atmospheric spurious signals at $\Theta = 2°$ are more important than at 1–30 arc min,[9] and even if very dry sites are chosen for ground-based experiments it is quite difficult to obtain satisfactory results.[30] However, changes in the flight route direction limited, in our case, the available time to about 20 min for each observed sky region.

The measurements allowed us to set upper limits on the CB anisotropy ranging from $\Delta T/T < 10^{-3}$ to $\Delta T/T < 3\times10^{-4}$ in various spots of the sky. Disregarding the measurements in zones very close to the galactic plane, no evidence of anisotropy has been found. The cosmological consequences of the present results are discussed in Sec. IV.

II. INSTRUMENTATION

The instrument employed in the present experiment is an airborne version of the radiometer previously used in high-mountain observations of the CB spectrum.[31] It consists of the following main parts (see Fig. 1):

(1) A wobbling mirror, capable of switching a $2°\times2°$ beam at a frequency of 20 Hz. The amplitude of the sinusoidal mirror oscillation is $2°$, and the plane of vibrations can be rotated with respect to the horizon in order to minimize the atmospheric gradient. The radiation coming through an aircraft window is reflected into the wobbling mirror by a flat mirror, gyrostabilized to within a few seconds of arc.

(2) A helium-cooled Germanium bolometer (of area 1 cm^2) coupled to an optical system having a field of view of $2°\times2°$ (at 80% of maximum) defined by a set of diaphragms. The optics consists of a f/4 TPX lens and a copper cone. At the bottom of the cone the bolometer is located in an integrating hemisphere. The throughput of the system is 6×10^{-2} cm^2 sr, and the noise equivalent power (NEP) about 5×10^{-14} W Hz$^{-1/2}$.

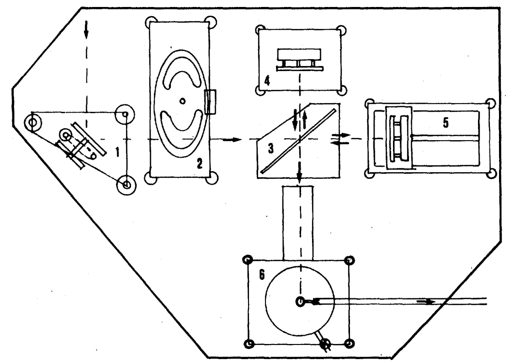

FIG. 1. Sketch of the infrared airborne radiometer. (1) Wobbling mirror, (2) chopper for absolute measurements, (3) beam splitter, (4) fixed mirror, (5) moving mirror, (6) liquid helium bolometer, and (7) pumping line for liquid helium.

(3) A double-lame reflecting chopper for absolute calibration and atmospheric measurements, rotating at a frequency of 20 Hz. The chopper does not operate in the course of the CB measurements. It is used to compare the atmospheric emission with a reference source at room temperature and at liquid-nitrogen temperature.

(4) A Michelson interferometer with a mylar beamsplitter operating in the 400–3000 μm range. The moving mirror of the interferometer is mounted on a Leitz stepping-motor screw. The interferometer can operate automatically in a continuous manner, at a sample rate of 150 μm, producing a 10-cm interferogram every 3 min. The efficiency of the interferometer is about 10%. We used the interferometer only for the study of the atmospheric spectrum.

(5) The electronic channel consists of a 10^3 X amplifier, two lock-ins with a relative phase shift of $90°$, and the on-board facilities of the ADDAS system, which allows AD conversion and magnetic storage of data. We used two phase-shifted lock-ins both for reliability and in order to discriminate the sky signals from the noise of the apparatus following the lock-ins.

Each set of observations consisted of the following steps:

(a) in-flight calibration with 77 K and 300 K blackbodies,

(b) spectral calibration,

(c) measurements of the atmospheric emission spectrum,

(d) measurements of the CB anisotropies,

(e) measurements of the atmospheric emission as in (c),

(f) spectral calibration as in (b).

The instrument was calibrated at ground and in flight with the following procedure. Keeping the wobbling mirror fixed and rotating the chopper we measured the difference between the radiances of a 297-K blackbody (a large piece of ecosorb) and a 77-K blackbody. We found that the broadband responsivity of the instrument is

$$S = 1.68 \pm 0.12\ \mu\text{V/K}, \quad 400\ \mu < \lambda < 2000\ \mu .$$

The spectral responsivity was measured by operating the Michelson interferometer into the instrument optics. Spectral elements of 0.1 cm^{-1} were observed (see Fig. 2). No appreciable change of responsivity was found in the calibrations, which were repeated during each flight. During the last two flights we were able to observe the Sun in order to determine both the angular response and the responsivity S of the system with the wobbling mirror operating. The angular response is shown in Fig. 3. The responsivity S is consistent with that measured by means of the rotating chopper if we assume a solar temperature of 4500 K. The solar temperature in the far infrared is not known with high accuracy, but the value assumed here is consistent with the convolution of the HSRA model,[32] with the spectral responsivity of our system, and with data obtained by Dall'Oglio *et al.*[33] and Müller *et al.*[34] A detailed spectral computation of the solar emission in the far infrared will be published elsewhere.

Two important sources of noise are encountered in airborne operations, i.e., electrical noise and mechanical noise. The electrical noise has been reduced to a negligible level by carefully isolating the liquid helium Dewar from the base plate. The mechanical noise has been found to be very important at the lock-in demodulator. After a careful selection of the less microphonic lock-ins we were

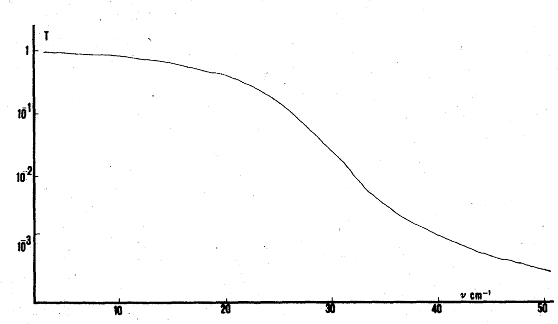

FIG. 2. Transmittance of the filters employed in the present experiment. The responsivity of the bolometer is almost flat up to 1.5 mm of wavelength.

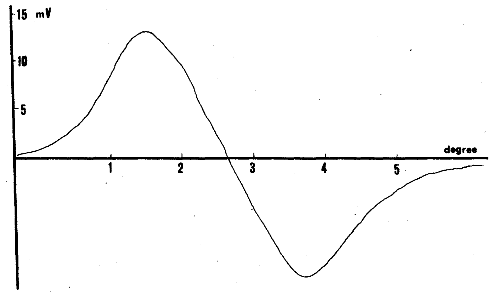

FIG. 3. Typical sun transit showing the angular response of the instrument for a 0.5° source.

able to reduce it to a reasonable level, although one of our lock-ins was more noisy than the other by a factor of 3. During the flights the field lens was covered by an opaque screen of ecosorb producing a blackbody cavity at ambient temperature, and the detector noise was recorded in such conditions for a time comparable with the observation of a single sky region (see the next section).

III. DATA ANALYSIS

Useful data were obtained in all of the 10 flights. However, we limit our analysis to the sky regions explored long enough to give significant information about the sky roughness. Somewhat arbitrarily, we pick up the regions where the observing time was long enough to reach a sensitivity $\Delta T/T < 10^{-3}$. Since the direction of motion of the airplane was often changed for the requirements of other on-board experiments, we could reach the above level of sensitivity only in flights 3 and 4 (May 18 and 19, respectively). The data collected during other flights were extremely useful to calibrate and test the instrumentation. We obtained more than one hundred atmospheric spectra and about fifty solar spectra. The analysis of data has been done as follows.

First the data were visually inspected to pick up the large spurious signals. These have been found to be correlated with important movements of the airplane, and have been eliminated simply by disregarding the data collected a few seconds before and after the airplane movements. Owing to the large oscillation amplitude of the wobbling mirror, it was impossible to avoid the presence of a constant offset in the output signal. In order to separate the offset fluctuations from the real sky signals we used a sinusoidal modulation and two lock-ins (90° apart in phase) which, respectively, minimized and maximized the offset. Any change in the first lock-in accompanied by a much larger change in the second one may be reasonably attributed to offset fluctuations. Fortunately, the offset remained very stable, and the detector noise was essentially the same as the one measured with an opaque screen covering the field lens.

The next step in the data analysis was the collection of data in "regions", each of them being characterized by a constant airplane direction and by an observing time long enough to observe various adjacent $2°\times 2°$ sky spots. The optimal regions were observed for about 20 min., corresponding to a set of 150 data. We found five useful regions in flight 3, and three useful regions in flight 4. The data in each region were then averaged over 8 min. (that is, over angles of 2°). At this stage the data consisted of the detector output after synchronous demodulation (in volts). The detector output can be expressed as

$$S = RT_A T_W \{I_A(1) + I_B(1) + I_L(1) - [I_A(2) + I_B(2) + I_L(2)]\} + S_N . \quad (1)$$

In this equation R denotes the responsivity, T_A the atmospheric transmittance, T_W the transmittance of the airplane window (Fig. 4), I_A the atmospheric radiation, I_B the CB radiation, I_L the local radiation spuriously reflected into the detector beam, and (1) and (2) denote two adjacent beam positions in the sky. S_N is the detector intrinsic noise, which in our case coincides with the noise recorded when the detector is pointing at a room-temperature blackbody. The CB anisotropy is given by

$$\sigma_B{}^2 = \tfrac{1}{2}\,\mathrm{var}[I_B(1) - I_B(2)] ,$$

whereas $\frac{1}{2}\,\mathrm{var}[I_A(1) - I_A(2)]$ and $\frac{1}{2}\,\mathrm{var}[I_L(1) - I_L(2)]$ are the atmospheric and local noise, respectively. The radiation emitted by the interior of the airplane is partially reflected by the airplane window into the field of view of the detector: As the wobbling mirror oscillates it explores different parts of the airplane, producing a spurious signal. The same effect arises if the mirror oscillates in such a way as to detect a gradient in the atmospheric emission. The total offset can be canceled with an appropriate choice of the oscillation direction. However, offset fluctuations would appear as a noise excess which may simulate a CB anisotropy. The local contribution is almost the same at ground and in flight, while the atmospheric contribution changes substantially. After careful shielding of the instrument the local noise has been found to be undetectable. The atmospheric noise at airborne altitude has been studied at shorter wavelengths[35] and a rough extrapolation suggests that it should be negligible. In fact during the flight we clearly detected an excess of atmospheric noise only in the presence of stratospheric clouds, whose spectra will be published elsewhere. Therefore both local and atmospheric noise were generally negligible, and the CB anisotropy is given by

$$\sigma_B{}^2 = \frac{1}{2}\left[\mathrm{var}\left(\frac{S}{RT_A T_W}\right) - \mathrm{var}\left(\frac{S_N}{RT_A T_W}\right)\right] . \quad (2)$$

Various methods have been proposed in the literature in order to subtract the detector noise, but all of them require a considerable amount of data. In our case it was preferable to give as an upper limit the total variance

$$\sigma_B{}^2 = \tfrac{1}{2}\,\mathrm{var}\left(\frac{S}{RT_A T_W}\right) . \quad (3)$$

To be very precise, the responsivity appearing in Eq. (3) is expected to be smaller than the one we measured in the laboratory by means of the extended blackbody because of the partial beam overlap in the differential measurements. Calculations made using the beam profile show that the correction is certainly smaller than 15%. Note also the consistency with the in-flight calibration where the Sun was used as a standard source. The intrinsic noise of the detector, measured in the laboratory by covering its field lens with an ambient-temperature blackbody, is

$$S_N = 17.5 \pm 0.5\ \mathrm{nV\,Hz^{-1/2}} ,$$

and corresponds to the noise equivalent temperature

$$\mathrm{NET} = 9.8 \mp 0.6\ \mathrm{mK\,Hz^{-1/2}}, \quad \text{at } T = 3\ \mathrm{K} .$$

However, the noise during the flight was greater than this value owing to the detector microphonics and to the noise excess found in one of the lock-ins. In about 20 min. of observation we were able to reach a sensitivity $\Delta T/T = 6\times 10^{-4}$ in flight 3, and 3×10^{-4} in flight 4 at one standard deviation.

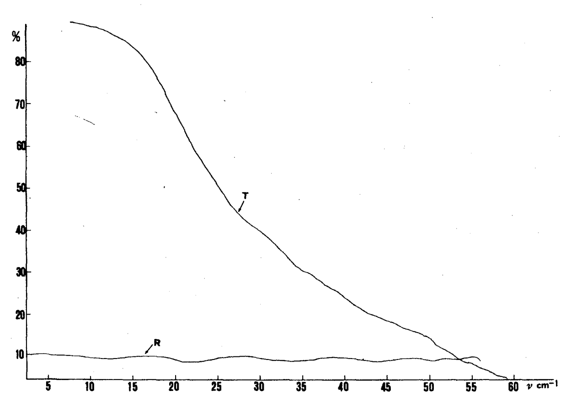

FIG. 4. Transmittance and reflectance of the airborne polyethylene window. No difference has been found before and after exposure to solar UV radiation, although the color changed significantly in the visible.

TABLE I. Data of flight 3.

Region	Time (min)	δ (deg)	α (h)	Number of useful points	$\Delta T/T$ at 1σ
1	0	4.22	7.57	192	5×10^{-4}
	8	4.37	7.70		
	16	4.58	7.83		
	24	5.51	7.91		
	32	5.92	7.89		
2	40	27.17	8.53	130	6×10^{-4}
	48	27.91	8.85		
	52	29.18	9.22		
3	60	−16.97	19.51	156	5.5×10^{-4}
	68	−17.47	19.57		
	74	−18.27	19.63		
	82	−19.60	19.76		
4	90	6.84	21.77	101	6.7×10^{-4}
		5.88	21.86		
5	98	−36.61	18.56	158	9×10^{-4}
	106	−37.29	18.55		
	114	−37.69	18.59		
	122	−38.21	18.59		
	130	−38.91	18.59		
	138	−39.54	18.49		

The data, corrected to temperature fluctuations through the on-board detector responsivity, are shown in Tables I and II.

First, let us discuss the results in region 5 of flight 3 and region 3 of flight 4, where the variance is much larger than the detector noise. The two sky regions are very close together, and at a distance of only a few degrees (2° and 3°, respectively) from the galactic plane. These facts suggest that the effect is real and related to dust emission. This point deserves more attention, since galactic emission may be a serious problem in CB measurements. Weiss[27] suggested that CB anisotropies cannot be easily discriminated from dust emission in the millimetric region. Although we have only few data relative to one sky region, we shall try to obtain information on the spatial and spectral distribution of grain emission in the far infrared. Ryter *et al.*[28] proved that dust in the galactic plane emits radiation between 50 and 200 μm, thereby producing a significant background over spatial dimensions of at least 0.7°. At the same galactic longitude of our observations but in the galactic plane Pipher[29] found a background of 7×10^{-8} W cm^{-2} sr^{-1} at 100–200 μm. Almost in the same direction Smoot *et al.*[22] found a temperature excess of 1 mK at a wavelength of 0.9 cm. Despite the differences in spectral regions and beamwidths let us try some comparisons. If the extension of the dust zone is about 1°, then Smoot's observation implies an absorption index $n<1$, which is rather surprising for interstellar grains ($1<n<3$). However, the signal at 0.9 cm may be due to synchrotron emission. If, on the other hand, we normalize the data of Pipher to our wavelength band and assume that the emission is extended over at least 1° outside the galactic plane, comparison with our data gives $n \gtrsim 2$. If

TABLE II. Data of flight 4.

Region	Time (min)	δ (deg)	α (h)	Number of useful points	$\Delta T/T$ at 1σ
1	0	43.31	20.84	100	2.7×10^{-4}
	8	42.04	21.24		
2	16	−34.87	15.35	100	3×10^{-4}
	24	−33.24	15.11		
3	32	−36.88	18.70	200	6.8×10^{-3}
	40	−37.44	18.62		
	48	−38.16	18.61		
	56	−38.65	18.67		
	64	−39.21	18.68		

we assume a more conservative value $n = 1.5$, dust emission 2° outside the galactic plane is at least four times smaller than in the plane itself. A rough extrapolation leads us to the conclusion that at a galactic latitude of 10° the contribution of dust to the background anisotropy in the millimetric region should be smaller than 10^{-4} K. Higher values of n imply smaller contributions at such longitude. Although a map of our galaxy in the millimetric region is required in order to reach convincing conclusions, our considerations suggest that the CB anisotropies at 1 mm can probably be investigated at high levels of sensitivity.

Regions 1–4 of flight 3 and regions 1 and 2 of flight 4 show variances consistent with the detector noise. Therefore, atmospheric noise (if any) and CB anisotropies are smaller than this. The best of the results in Table I gives an upper limit on the CB anisotropies $\Delta T/T < 3\times 10^{-4}$ at $\Theta = 2^\circ$.

IV. DISCUSSION

In this section we shall discuss the cosmological implications of the upper limit

$$\Delta T/T < 3\times 10^{-4}, \tag{4}$$

which has been established at $\Theta = 2^\circ$ and one standard deviation, for the CB anisotropy. As anticipated in the Introduction, from (4) we are able to derive upper limits on the amplitude of density fluctuations, whirl motions, and gravitational waves at a scale of $\sim 10^2 \times \Omega_0^{-1}$ Mpc. Different limits can be established depending on the red shift at which the background radiation ceased interacting with matter. Therefore we shall consider two cases: (i) The optical depth of the cosmological plasma due to the secondary ionization (reheating) was $\tau_p < 1$, so that the last scattering of most of the CB radiation occurred at the recombination of hydrogen, red-shift $z \simeq 10^3$ (case HI); (ii) The optical depth was $\tau_p > 1$ and the last scattering occurred at $z \simeq 13\Omega_0^{-1/3}$ (case HII). The latter alternative is possible if the reheating took place at rather early times. Let us consider separately the kinds of perturbations mentioned above.

a. Density perturbations. The influence of density waves on the CB anisotropy has been discussed by various authors, who consider Doppler-shift effects[15,20] and gravitational-potential effects.[11,16,20] From their results and the present upper limit, which we shall take at three standard deviations ($\Delta T/T < 10^{-3}$), we get

$$\left(\frac{\Delta\rho}{\rho}\right)_l \lesssim 2\times 10^{-3}\Omega_0^{1/2}, \quad \left(\frac{\Delta\rho}{\rho}\right)_0 \lesssim 2\Omega_0^{3/2} \qquad \text{(case HI)}, \tag{5}$$

and

$$\left(\frac{\Delta\rho}{\rho}\right)_l \lesssim 0.3\Omega_0^{5/3}, \quad \left(\frac{\Delta\rho}{\rho}\right)_0 \lesssim 4\Omega_0^{7/3} \qquad \text{(case HII)}, \tag{6}$$

where $\Delta\rho/\rho$ is the amplitude of the density contrast; here and henceforth the subscripts $_0$ and $_l$ denote the present epoch and the last scattering epoch, respectively. The limit we can set on $(\Delta\rho/\rho)_0$ is not very stringent if $\Omega_0 = 1$. However, the value $\Omega_0 = 0.1$ is preferred for the reasons given by Gott *et al.*[36] In such a case we would conclude that $(\Delta\rho/\rho)_0 \lesssim 0.1$ at scale $L_0 = 10^3$ Mpc. This result does not exclude the existence of superclusters, although it does not seem to be compatible with inhomogeneities as large as claimed by Chincarini.[37] Moreover, it clearly argues against the ideas of chaotic cosmology.

b. Whirl motions. Vortex perturbations should obviously affect the CB isotropy through Doppler shift. From the result of Anile and Motta[17] we get in the present case the upper limits

$$\frac{\omega_l}{H_l} \lesssim 5\times 10^{-4}\Omega_0^{1/2}, \quad \frac{\omega_0}{H_0} \lesssim 2\times 10^{-5}\Omega_0 \qquad \text{(case HI)}, \tag{7}$$

and

$$\frac{\omega_l}{H_l} \lesssim 1\times 10^{-2}\Omega_0, \quad \frac{\omega_0}{H_0} \lesssim 3\times 10^{-3}\Omega_0^{5/3} \qquad \text{(case HII)}, \tag{8}$$

where ω is the vorticity of matter and H the Hubble constant. Thus the global velocities of matter at scales $L_0 \simeq 10^2\Omega_0^{-1}$ Mpc should be smaller than $v = 5\times 10^{-5}\Omega_0^{2/3}c$. The number of revolutions performed by a matter vortex since the big bang is $n \simeq \omega^*/H^*$, where ω^* and H^* are calculated at the epoch when the densities of matter and radiation equalize, namely at $z^* \simeq 10^4\Omega_0$. Since $\omega^*/H^* \simeq 10^2\Omega_0^{1/2}\omega_0/H_0$ from Eq. (8) we find that the total number of revolutions is less than $\sim\Omega_0^2$ at the scale $10^2\Omega_0^{-1}$ Mpc. If Eq. (7) applies, then $n \lesssim 2\times 10^{-3}\Omega_0^{3/2}$. In any case the vorticity of matter is small at the present epoch. For typical cosmological observers the Mach principle should be satisfied at such scales at least up to rotations $\omega_0 \sim 10^{-6}\Omega_0^{5/3}$ arcsec/century. This limit does not apply to an earthly observer, if the vorticity in our neighborhood is not a typical one. An upper limit on the local vorticity can be obtained directly from measurements of the large-scale anisotropy of the CB radiation.[38]

c. Gravitational waves. Simple expressions relating the CB anisotropy to the amplitude of low-frequency gravitational waves can be derived from the integral expression of Ref. 20. Since explicit results have not yet been given in the literature for $\Omega_0 \neq 1$ Friedmann models, we shall give them here. We have (cf. Ref. 21)

$$\frac{\Delta T}{T} \simeq \Omega_0 z_l \left(\frac{H_0 L_0}{2\pi c}\right)^2 h_l \simeq \Omega_0 z_l h_0 \quad \text{(case HI)}, \tag{9}$$

$$\frac{\Delta T}{T} \simeq \tfrac{1}{2} N^{-1/2} h_l \simeq \frac{\Omega_0 z_l}{2} N^{-1/2} h_0 \quad \text{(case HII)}, \tag{10}$$

where h and L are the amplitude and wavelength, respectively, of the gravitational wave and N is the number of wavelengths contained in the last-scattering thickness. From Eqs. (9) and (10) we find

$$\left.\begin{array}{l} h_l \lesssim 7\times 10^{-3}\Omega_0 \\ h_0 \lesssim 1\times 10^{-6}\Omega_0^{-1} \end{array}\right\} \text{(case HI)}, \tag{11}$$

and

$$\left.\begin{array}{l} h \lesssim 7\times 10^{-3}\Omega_0^{1/3} \\ h_0 \lesssim 4\times 10^{-4}\Omega_0^{-1/3} \end{array}\right\} \text{(case HII)}. \tag{12}$$

We can conclude that at scales $L_0 \simeq 10^2 \Omega_0^{-1}$ Mpc the gravitational wave amplitude is $h_0 < 10^{-3}$. This implies that the equivalent mass density is less than $10^{-5}\rho_c$, where $\rho_c \simeq 5\times 10^{-30}$ g cm^{-3} is the critical mass of the Friedmann cosmology. By taking into account also upper limits obtained at other scales,[16,39] we conclude that long-wavelength gravitational radiation does not play a relevant role in the global dynamics of the universe at the present epoch. Considering the limits given by Eqs. (5)–(12) altogether, we can conclude that the universe was very regular at the last-scattering epoch at a scale slightly larger than the optical horizon.

V. CONCLUSION

According to the present measurement, the CB anisotropy is very small even at a scale $\Theta = 2°$, where primordial ($z > 10^3$) dissipative phenomena played no role. This suggests that the CB anisotropy may be extremely small at all scales (except the dipole scale). The universe looks very regular at large scales.

The necessity of reaching a level of sensitivity of 10^{-5} seems to be cogent. Fortunately, according to our results the main obstacle for millimetric measurement at such a level of sensitivity, i.e., the galactic background, seems to be not so serious, if one takes care to avoid sky regions close to the galactic plane.

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